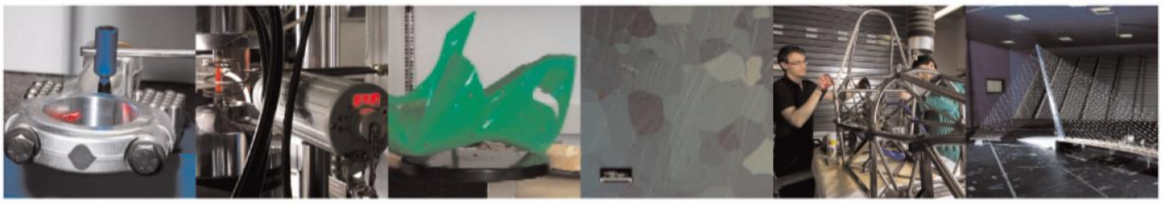


# Wear behaviour of PVD coated and cryogenically treated tools for Ti-6Al-4V turning

Strano, Matteo; Albertelli, Paolo; Chiappini, Elio; Tirelli, Stefano

This is a post-peer-review, pre-copyedit version of an article published in INTERNATIONAL JOURNAL OF MATERIAL FORMING. The final authenticated version is available online at: http://dx.doi.org/10.1007/s12289-014-1215-6

# Wear behaviour of PVD coated and cryogenically treated tools for Ti-6Al-4V turning

Matteo Strano [1,*]

Email matteo.strano@polimi.it

Paolo Albertelli [1]

Email paolo.albertelli@polimi.it

Elio Chiappini [2]

Email elio.chiappini@musp.it

Stefano Tirelli [2]

Email stefano.tirelli@musp.it

[1] Dipartimento di Meccanica, Politecnico di Milano, via La Masa 1, 20156 Milano, Italy

AQ1

[2] Laboratory Macchine Utensili e Sistemi di Produzione, MUSP, via Tirotti 9, Piacenza, Italy

---

## Abstract

Titanium alloys, mainly because of their poor thermal conductivity, need to be cut at relatively low cutting speeds, with obvious negative consequences on the profitability of machining. An important amount of research has been done in order to increase productivity in titanium machining operations: high performance coatings and innovative technologies to improve insert resistance to wear represent promising solutions. In this work, a highly performing cutting insert (coated with a TiAlN layer obtained by *Physical Vapor Deposition* (PVD) magnetron sputtering) has been tested against the option of applying a Deep Cryogenic Treatment (DCT), when used for rough turning of aerospace titanium. The effects of the DCT have been experimentally investigated with two different experimental plans at low and high cutting speeds (respectively $v_c \leq 50$ m/min, $v_c \geq 60$ m/min). Statistical analyses of the results have been performed. The results show that at low cutting speed, the DCT treatment does not increase the tool life. At higher values of $v_c$, flank wear vs. time curves of coated tools have been determined, with and without DCT, and they clearly show that cryogenically treated tools present better wear resistance at higher cutting speeds. The wear mechanisms on the rake face and the flank for these two TiAlN coated tools have been analysed using a scanning electron microscope. The adhesion of titanium on the tool surface is lower for a DCT treated insert. The results indicate that the hardening of tools induced by the cryogenic treatment improves their useful life in high rate machining of titanium.

## Keywords

Ti6Al4V
Turning
Deep cryogenic treatment
Magnetron sputtering
PVD
Titanium alloys
Tool wear

# Introduction and state of the art

Titanium alloys present many interesting mechanical properties (such as very high strength to weight ratio, high toughness, biocompatibility and good corrosion resistance) that promote the use of these materials not only in the aerospace industry, but also for bio-medical applications and for the chemical and oil & gas industries. Conversely, titanium alloys are classified as “difficult to machine” materials especially due to their low thermal conductivity, which is one of the most important material characteristics when considering machinability [1]. Furthermore, titanium shows low elastic modulus and high chemical reactivity [2]. Among several problems encountered in titanium machining, early tool failure due to excessive wear represents one of the most critical issues.

High cutting performance is strongly needed in aerospace manufacturing, where generally rough machining may remove up to 90 % of the material from the blank, even in small parts production. This manufacturing approach is typically adopted due to the high costs of titanium forgings and to the fact that dedicated dies are not economically feasible, because of small production batches. So far, a lot of research has been done to study and to improve the performance of carbide tools in titanium machining.

The geometrical features of carbide inserts strongly affects the required cutting forces, the temperature distribution close to the cutting region and consequently the tool wear rate. In terms of productivity, a round tool with sharp cutting edge can remove a greater quantity of material thanks to the variable chip thickness along the cutting edge, that allows higher feed rates. A small hone radius, entailing both lower cutting forces and temperatures, ensures tool life enhancement [3, 4].

The most common wear mechanisms involved in machining of titanium alloys are: adhesion of the processed material to the insert, coating delamination, plastic deformation and chemical diffusion of tungsten and cobalt from the tool to the workpiece [5].

Cubic Boron Nitride (cBN) tools have been very often used for prolonging the tool life when working aerospace alloys, such as inconel or titanium. Ezugwu et al. [6] observed that, in turning operations, cBN tools showed poor performance compared to Tungsten Carbide uncoated inserts. Single or multi-layer insert coating (with nitrides, oxides, cBN or carbides) allowed a strong improvement in tool life. Several authors studied the performance of different types of coating in Ti-6Al-4V turning and milling operations.

Ozel et al. [7] discovered that tools with multi-layer coating (TiAlN and cBN) present a higher wear resistance than uncoated, TiAlN or cBN single layer coated tool. Although multi-layer coatings cause greater cutting forces, they represent a valid solution to improve Ti6Al4V dry cutting.

Jawaid et al. [8] tested two types of inserts in Ti6Al4V milling: TiN coated tool and TiCN + $Al_2O_3$ coated tool. The second one gave better performance in terms of tool life.

The literature includes also works concerning innovative coatings, tested for Ti6Al4V machining: niobium nitride (NbN), aluminium chromium nitride (AlCrN) [9], coatings obtained by multi-layer combinations of nitrides and oxides [10], diamond+TiB2+CrN/DLC [11]. However, not all the developed coatings are able to improve tool life. As an example, Srivastava et al. [12] tested different coatings (composed of nano-layers of TiAlSiCN, CrAlSiN-CrAlSiYN, TiAlN-CrN), which were not specifically designed for titanium, in high speed Ti6Al4V turning. Their experimental tests showed that those coatings were not able both to extend tool life and to significantly reduce cutting forces compared to uncoated WC inserts. Liu et al. [13] studied the effect of two nanocomposite coatings in dry and MQL (minimal quantity lubrication) conditions.

The high ionization magnetron sputtering coating technology has been known for years [14] as an option for enhancing productivity in machining of hard materials. Not many papers have studied this kind of coating in Ti6Al4V cutting and they generally deal with dry cutting conditions [15] in order to accelerate machining tests and to reduce the experimental costs. On the contrary, in this paper, standard industrial flood emulsion lubrication will be used. The commercial availability of high ionization magnetron sputtering tools is still relatively limited and they cannot yet be considered commercial standards. For this reason, in order to better appreciate the results with respect to the typical industrial scenario, a widely used “standard” insert will be included in the present study, used as a reference benchmark.

### *Cryogenic treatment of cutting inserts*

Liquid nitrogen with its boiling temperature of −196 °C can be used in machining operations for two purposes. The first one is to obtain a strong cooling effect at the cutting zone by delivering cryogenic fluid. The literature offers plenty of papers about cryogenics in machining but the first authors which performed this kind of experimentation are Evans et al. [16] who found that tool wear can be significantly reduced by machining ferrous materials at extremely low temperatures. The second application of cryogenics is the thermal treatment of tools. Cryogenic treatments of cutting inserts can be classified as follows: Deep Cryogenic Treatments (DCT) or Shallow Cryogenic Treatments (SCT). A different minimum tool cooling temperature is used in the two mentioned treatments: −196 °C for DCT and −80 °C for SCT. The available literature does not include studies regarding the use of cryogenically treated inserts in machining of titanium alloys, as confirmed by a recent state of the art review [17]. Cryogenic treatments are a quite recent development, that have already been tested with interesting results in machining of steels [18] and other materials. Substantial improvements in tool life using SCT treated inserts in steel machining were found by Gill et al. [19, 20]: the maximum tool life enhancement, over untreated inserts, was about 25 %. The authors also compared SCT and DCT on tungsten carbide TiAlN coated inserts: it was observed that the deep cryogenic treatment entails a cutting performance decay, especially at lower cutting speeds. However, at higher cutting speeds, marginal gain in tool life can be obtained. Yong et al. [21, 22] agreed that cryogenic treatment could improve flank wear and chipping resistance although cryogenic inserts tend to lose their superior properties during long and uninterrupted cutting operations and prolonged exposure to high temperatures. Furthermore hardness and compression strength increase with cryogenic treatment [23]. Gill et al. [24] observed that cryogenically treated tungsten carbide inserts performed better than untreated ones during wet machining of C60 both in continuous and interrupted machining mode. Moreover, the cryogenically treated tungsten carbide inserts, used under wet cutting conditions, improved the performances especially at higher cutting speeds.

Thakur et al. [25] observed that cryogenic treatment of WC tools has less effect on microstructure compared to traditional heat treatments but some physical changes take place and these changes are due to cobalt densification. The cobalt holds the carbide particles more firmly thereby increasing wear resistance. SreeramaReddy et al. [26] and Gill et al. [27] investigated microstructural changes of tungsten carbide tools by adopting cryogenic treatment before machining and they found that a fine eta (η) phase carbide appears during long exposure to cryogenic temperatures. These fine particles act as fillers along with the larger particles to form a denser, more coherent, and much tougher matrix in the material. The cryogenic treatment reduces the chemical degradation of the cobalt matrix at higher temperatures.

The goal of this paper is to fill some gaps that have been identified in the scientific literature as outlined above. Specifically, the purpose is to verify whether the life of a high performance insert (i.e., coated with a high ionization magnetron sputtering PVD layer) can be further increased by means of a cryogenic treatment, with special reference to Ti6Al4V cutting. The effects will be assessed in standard lubrication conditions within an industrially relevant range of working parameters, suited for rough turning. In fact, most studies on the performance of coatings are performed under unconventional conditions, e.g., with MQL or even in dry machining, and with very high values of cutting speed, which are not typical of rough turning of titanium alloys.

The paper is organised as follows: in the first part an experimental plan is presented and discussed, conducted at lower cutting speeds, where a high performance TiAlN coated insert will be tested against a DCT treatment and also compared to a benchmark tool, widely used in the industry for machining of aerospace titanium. Then a second experimental plan is presented, at higher cutting speeds, and the results will also be discussed with the aid of SEM observation of worn tools.

## Lathe turning tests at low cutting speed

An experimental plan has been designed, conducted and analysed in order to evaluate and compare the cutting performance of three different types of inserts for rough turning of Ti6Al4V. The inserts have been identified and labelled as “S”, “L” and “LC”.

- Insert “S” is a PVD coated carbide tool with coating layers TiAlN (2 μm) + AlCrO (0.7 μm), hardness 1878 HV, typically and widely used in the industry for machining of aerospace titanium.
- Insert “L” is the same as “S”, except for the coating: a thicker TiAlN film is applied, with an average thickness of 4.2 μm, deposited using high ionization magnetron sputtering technology, hardness 2037 HV (+8 % with respect to S).
- Insert “LC” is the same as “L”, but was also subject to a deep cryogenic treatment (DCT) with the aim of increasing its surface hardness, which goes up to 2259 HV (+11 % with respect to L).

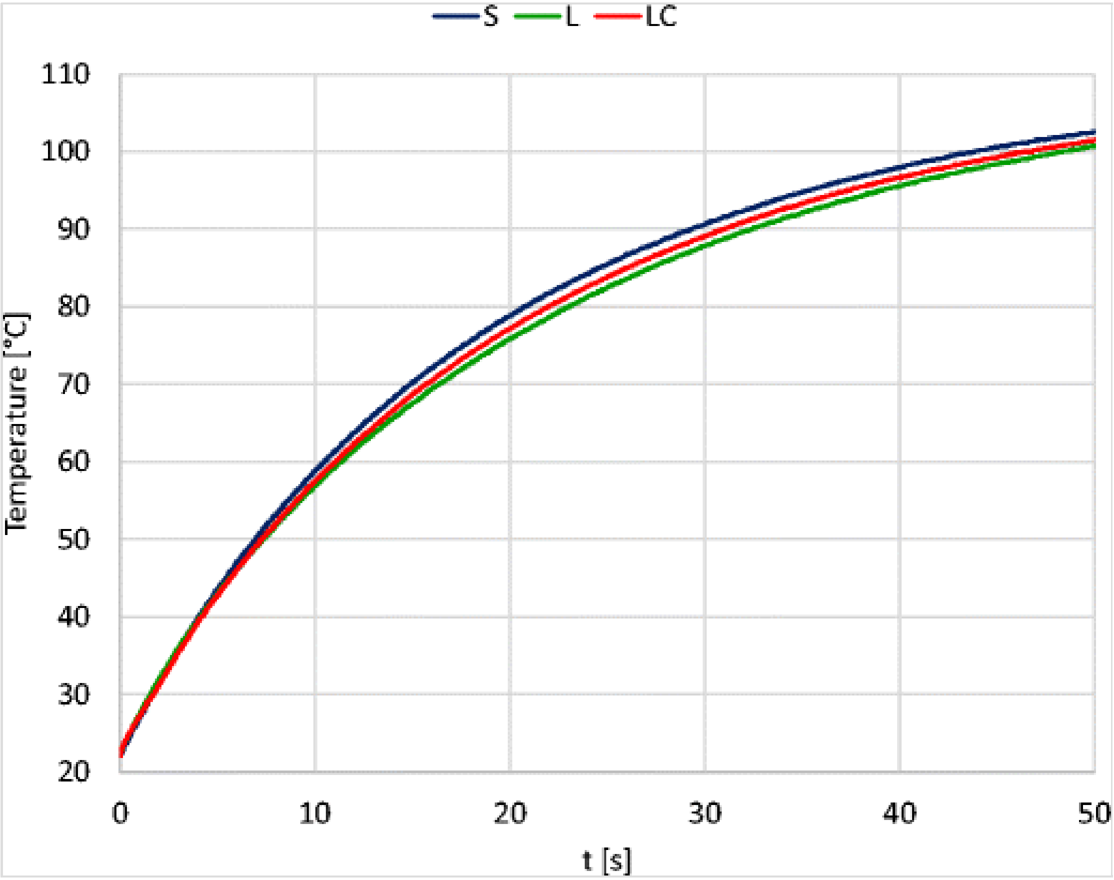
Hardness measurements of the inserts have been performed with a pressing load of 0.5 kg, selected in order to characterize the hardness of the entire tool including the WC and the coating layers. Each hardness value has been computed considering six repeated hardness measurements on the tool flank. It is important to note that, in order to compare only the surface properties of the tools, the three types of inserts are identical in geometry and angles. They also have the same material on the outer surface (TiAlN), hence they should exhibit the same tendency to oxidation and the same chemical affinity for adhesion of titanium. Due to a lower thickness of the coating, the standard S tool dissipates faster the heat received by the tool through conduction and generated by friction. As a proof, thermal conductivity tests have been carried out for the inserts: each type of insert has been heated by placing the tools, mounted on the tool holder, inside a furnace pre-heated at 110 °C. Their temperature was monitored using a thermocouple placed between the insert and the tool holder. The temperature curve, starting from ambient temperature, for each insert is proposed in Fig. 1. The thermal system has been modelled as a first-order system through the following equation [28]:

$$t \cdot \left(-\frac{1}{\tau}\right) = \ln\left(\frac{T - T_\infty}{T_0 - T_\infty}\right). \tag{1}$$

where $\tau$ is the time constant in minutes needed to reach 63.2 % of final temperature ($T_\infty = 110$ °C), starting from $T_0 = 20$ °C. The calculated time constants were: $\tau_s = 20.8$ min for insert S, $\tau_l = 23.1$ min for insert L and $\tau_{lc} = 22.5$ min for insert LC. Assuming homoscedasticity (constant variance) over time, a standard deviation on $\tau$ was calculated with value to 0.11 min, very small if compared to the calculated average $\tau$-values. As expected, insert S shows a slightly smaller time constant, i.e., a thermal conductivity higher of approximately 2–3 %, due to the higher thickness of the coated layer, whereas there is no appreciable difference between inserts L and LC. In other words, a first important conclusion is that the cryogenic treatment does not change the thermal behaviour of coated carbide tools (L vs. LC), which is conversely influenced by the type and thickness of the coating (L vs. S).

**Fig. 1**

Temperature curves for the three inserts



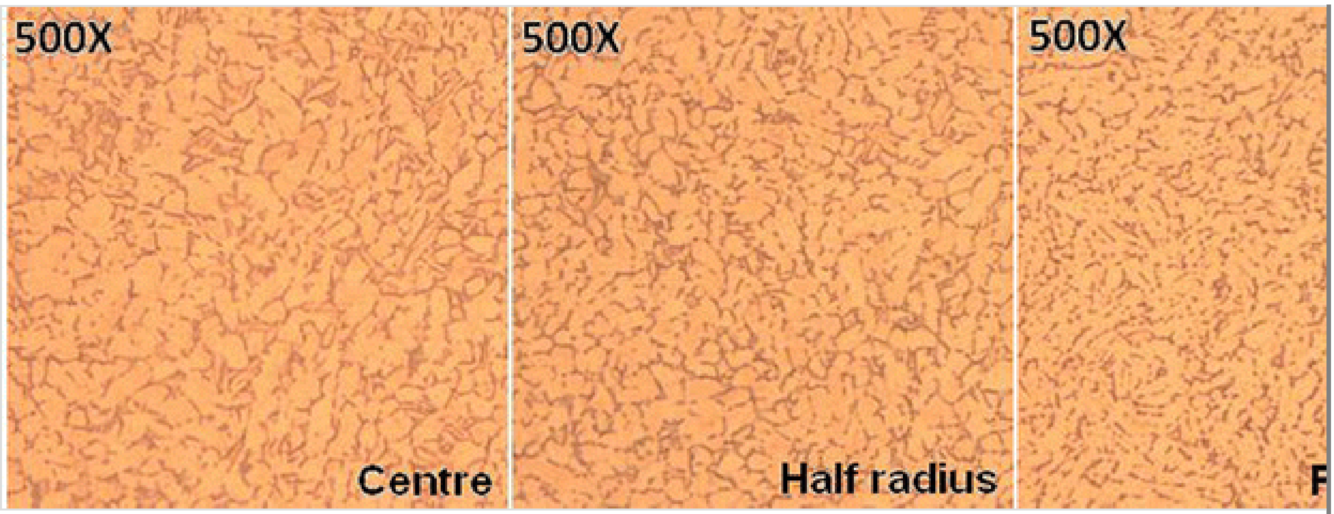
AQ2

### *Workpiece materials*

The mechanical properties of the as-received materials can be considered quite homogeneous along the bar diameter, since the material is annealed and since a micrographic analysis has shown that the microstructure is substantially uniform across the cross section of the bars (Fig. 2). Chemical composition and average mechanical properties are given in Tables 1 and 2.

**Fig. 2**

Micrograph of cross section of bar



### Table 1

Chemical composition of Ti6Al4V bars

| | %O | %N | %H | %C | %Fe | %Al | %V |
|---|---|---|---|---|---|---|---|
| Max | 0.18 | 0.008 | 0.002 | 0.019 | 0.12 | 6.54 | 4.11 |
| Min | 0.17 | 0.008 | 0.0018 | 0.016 | 0.08 | 6.52 | 4.00 |

### Table 2

Mechanical characterization of material

| Ti6Al4V titanium alloy bar with 55 mm diameter and 500 mm length | | | |
|---|---|---|---|
| Tensile Strength TS [MPa] | 933.67 | Elongation at fracture [%] | 18.01 |
| Yield Strength $Y_{S0.2\%}$ [MPa] | 866.94 | Post-fracture reduction of area [%] | 46.22 |

## *Experimental plan and procedures*

The experimental parameters have been selected according to a full factorial Design of Experiments (DOE) [29], with the following input factors: insert type, cutting speed $v_c$ and feed rate $f$. Their levels are listed in Table 3. The experimental plan consists of 4 tests (2 cutting speeds and 2 feed rates) for every tool with 2 replicates, for a total of 24 turning runs. The DOE has been designed in order that an Analysis of Variance (ANOVA) could be conducted on the response variables, i.e., on the output results of the tests. The following response variables have been measured and analysed:

**Table 3**

Machining parameters for turning tests

| Factors | No. of levels | Values |
|---|---|---|
| Cutting tools | 3 | Inserts “S”, “L”, “LC” |
| Cutting speeds ($v_c$) | 2 | 40 and 50 [m/min] |
| Feed rates (f) | 2 | 0.2 and 0.3 [mm/rev] |
| Depth of cut (b) | 1 | 1.2 [mm] |
| Cutting fluid | 1 | Hocut 795/I at a concentration of 5 % and a flow rate of 2 [l/min] |

- average flank wear $VB_B$,
- surface roughness $R_a$,
- cutting force ($F_c$), feed force ($F_f$), radial force ($F_r$)
- coefficient of friction μ
- chip segmentation frequency ($f_s$) and morphology

The ANOVA technique will be used as the statistical method to determine if each investigated factor significantly affects the measured responses. A I-type error threshold $\alpha = 0.01$ will be adopted for every F-test of the ANOVA table [29].

All turning tests were interrupted when a total volume of about 343,000 mm$^3$ had been removed from the workpiece: this volume was enough to reach an evident flank wear (and in some cases to cause tool failure) but it did not imply a large amount of material consumption. The total material volume was removed in the same way for every cutting test: two sets of 15 passes, each 82 mm long, with a depth of cut of 1.2 mm. The diameter of the bar was reduced from 55 to 19 mm. A tool failure criterion has been employed and established in accordance with ISO Standard 3685 for tool life testing. The criterion is based on the calculation of the average flank wear: the tool is considered to be worn out when it exceeds 0.3 mm.

As demonstrated by Hughes et al. [3], the micro-hardness material perturbation due to the previous cuts and passes (in Ti6Al4V turning) is quite limited and it affects only a small portion of the removed material, thus its effects can be ignored.

All machining trials have been conducted using a CNC Somab Unimab 400 lathe with a maximum spindle speed of 2560 rev/min and a drive motor rated up to 11 kW. In order to reproduce realistic production conditions cutting fluid Hocut 795/I at a concentration of 5 % and a flow rate of 2 l/min has been used. Cutting forces were acquired during the tests through a Kistler dynamometer that was interposed between the tool and the turret. Roughness measurements have been performed (using a TESA Rugosurf 20) on the machined surface only after the first pass, in order to avoid any influence of tool wear. Average flank wear was measured on micrographic images, taken using an optical stereomicroscope; the positioning reproducibility of the measured insert was guaranteed by a tool holder, fixed to the base of the microscope. Images have been analysed after being processed.

Friction coefficients were calculated starting from cutting, feed and radial forces and chip morphology was directly observed using the microscope.

## Results and discussion

In this section the effects of the investigated factors are analysed and critically discussed. First of all, the influence of cryogenic treatment on the tool life expectation have been compared in terms of tool flank wear $VB_B$, which is considered the most important response variable in the present study. Additional analyses have been conducted considering the cutting forces, the chip morphology and the tribological behaviour during cutting.

Finally, the Taylor’s wear law is experimentally determined in order to better evaluate the improvements induced by the DCT treatment.

### *Tool wear*

The average flank wear width was measured after a volume of about 343,000 $mm^3$ had been removed from the workpiece. The ANOVA tests (Table 4) show that factor “Ins” (type of insert), the cutting speed $v_c$, the feed rate f and the interactions “Ins-$v_c$” and “Ins-f” significantly affect the average flank wear, since their *p*-value is smaller than the tolerated error $\alpha = 0.01$. These interactions are mainly due to the behaviour of insert “S”, whose tool life is particularly short for higher values of f and $v_c$, due to a faster delamination or damaging of the coating. In order to better explain and compare the tool performances, the average flank wear measured at the end of each cutting test is reported in Fig. 3, vs. the material removal rates (MRR). The ANOVA table also yields, in its last row, the mean square (MS) error of the residuals, which is a statistical measure of the variance of all data. It is relatively large. However, if the analysis is repeated separately for insert S and for inserts L and LC, significantly different values are obtained. A clear indication of the average values and the variability of the $VB_b$ results can be obtained by looking at Fig. 3: the L and LC tools do not significantly differ from each other, in other words the cryogenic treatment has virtually no effect on the tool life, in the investigated range of cutting speed $v_c$, depth of cut b and feed rate f. To better appreciate the very small difference between the inserts L and LC, error bars are plotted equal to ± their pooled standard deviation. The results of the insert S are printed too: they show larger average wear and larger uncertainty of the results.

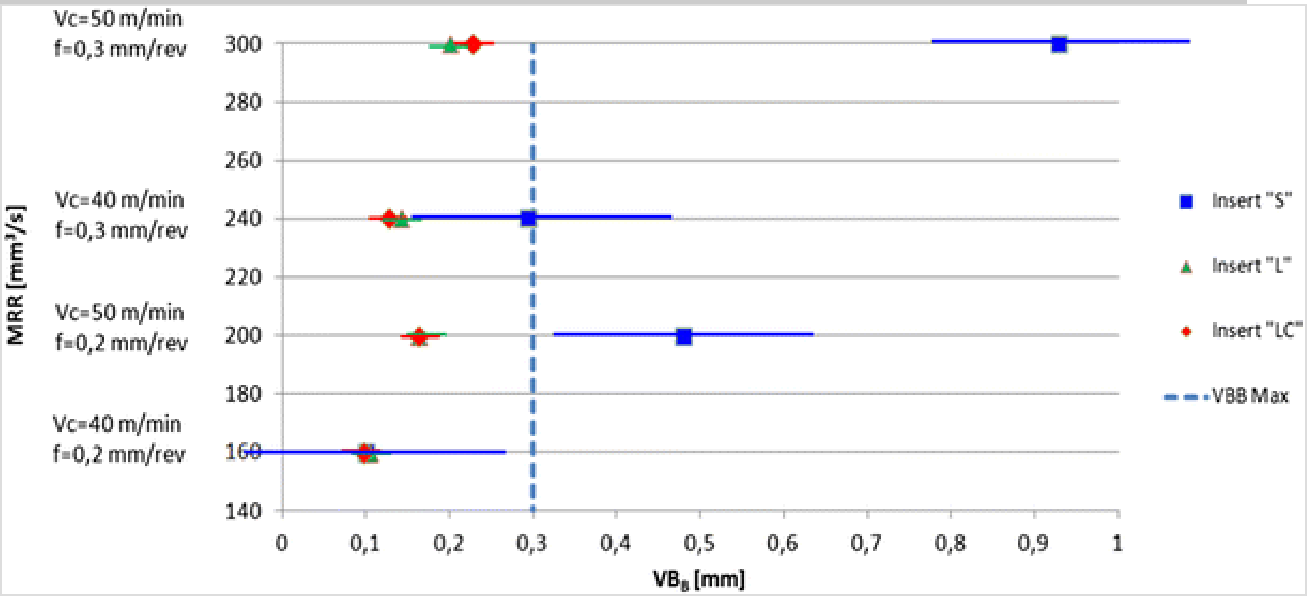
**Table 4**

ANOVA test results for $VB_B$; significant factors and interactions are printed in bold font

| Source | Seq SS | Adj SS | Adj MS | *F* | *p*-value |
|---|---|---|---|---|---|
| **Ins** | 0.470 | 0.470 | 0.235 | 40.970 | **0.000** |
| **$v_c$** | 0.282 | 0.282 | 0.282 | 49.100 | **0.000** |
| **f** | 0.110 | 0.110 | 0.110 | 19.160 | **0.002** |
| **Ins·$v_c$** | 0.255 | 0.255 | 0.127 | 22.180 | **0.000** |
| **Ins·f** | 0.103 | 0.103 | 0.052 | 8.980 | **0.007** |
| **$v_c$·a** | 0.014 | 0.014 | 0.014 | 2.470 | 0.151 |
| Error | 0.052 | 0.052 | 0.006 | | |

**Fig. 3**

Material removal rate MRR vs. $VB_B$ for every experimental test



The results show that insert “L” is an excellent choice, much better than the “S” insert, which is typically used with aerospace titanium in the industry. Unfortunately, the cryogenic treatment is not able to further improve its useful working life, at least in the investigated range of parameters, although the hardness of the LC inserts is higher.

In the remainder of this Section, it will be shown that there is, statistically, no difference between “L” and “LC” also on the other response variables of interest.

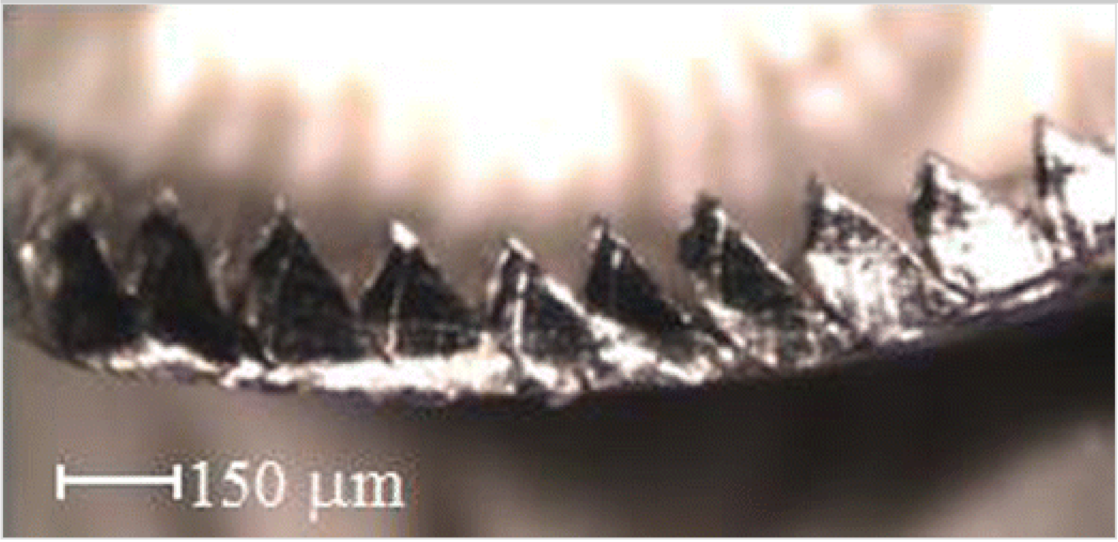
### *Cutting forces and chip morphology*

Average forces are calculated during the first period of each investigated machining condition, thus inserts are in no case heavily nor significantly worn. Data are purged from the increase in cutting forces that occurs when the insert is nearing the end of its life. In a way similar to what has already been shown with the aid of Table 4, the statistical significance of the factors has been tested with F-tests. The ANOVA test shows that the different coating of the tools does not significantly affect the main cutting force $F_c$, that is influenced only by the feed rate, with a negligible influence of the cutting speed. Radial ($F_r$) and feed ($F_f$) forces result significantly lower than the cutting force ($F_c$).

All cutting tests produced a segmented chip (Fig. 4). The three tested inserts do not produce chips with appreciable difference in shape and segmentation frequency. Segmentation frequency values range from about 2000 to 2700 Hz, with cutting speed being the only significant factor. A transition from a short washer-type helical chip to a twisted one is observed with the increase in tool wear.

**Fig. 4**

Chip morphology detail. Insert “LC”, Vc = 40 [m/min], f = 0.3 [mm/rev]



The shear angle ϕ was calculated for every test using collected samples of metal chips and with the aid of the Ernst-Merchant model. For every cutting condition the calculated shear angle was between 26° and 30°: this implies that the insert type does not alter the chip formation mechanism.

### *Tribological effects*

The coefficient of friction $\mu$ has been calculated using the cutting forces through Eq. (2).

$$\mu = \frac{F_n \cdot \cos\left(\gamma_r\right) + F_c \cdot sen\left(\gamma_r\right)}{F_c \cdot \cos\left(\gamma_r\right) - F_n \cdot sen\left(\gamma_r\right)}. \quad 2$$

where $F_c$ is the cutting force, $F_n$ is the normal force on the cutting plane defined by feed force ($F_f$) and radial force ($F_r$) as follows:

$$F_n = \sqrt{F_f + F_r}. \quad 3$$

$\gamma_r$ is the true rake angle and is defined as:

$$\gamma_r = \arcsin\left(\sin^2(\lambda) + \cos^2(\lambda) sin(\gamma)\right). \quad 4$$

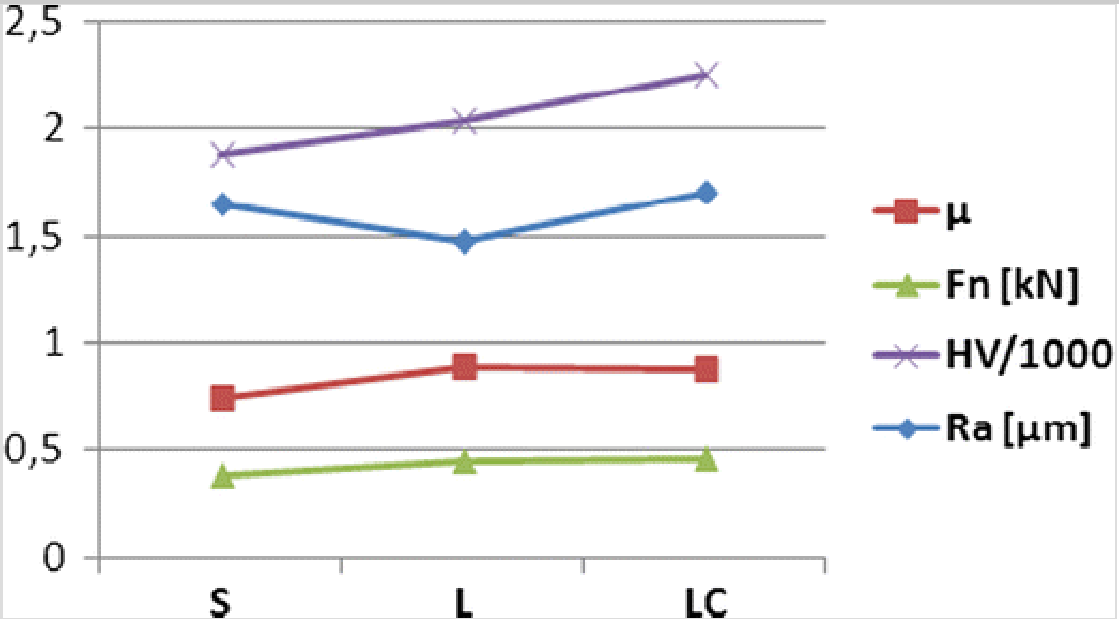
where λ is the top rake angle (equal to −6°).

As expected, the type of insert is a significant factor for μ, with a *p*-value of 0.01, but only because the “S” insert shows a lower value: no effect on friction is due to the DCT. Incidentally, the feed rate is also significant: when increasing f from 0.2 to 0.3 mm/rev, the friction coefficient decreases from a value of about 0.91 down to 0.76.

Finally, the average workpiece roughness Ra was measured twice during each cutting test: when half (171,500 $mm^3$) and all (343,000 $mm^3$) of the total volume has been removed. Insert type does not significantly affect the roughness value measured halfway, as shown in Fig. 5, where the average values of some important variables are printed. However, the surface roughness values at the end of machining tests are significantly affected by the type of insert, because of the different wear level reached by different inserts. The highest final surface roughness value was 3.3 μm, obtained when machining at a cutting speed of 50 m/min and feed rate 0.3 mm/rev using insert “S”. These results clearly confirm that coating delamination and nose chipping for inserts L and LC began later than insert S. Again, no significant difference can be appreciated on the surface quality before and after the cryogenic treatment.

**Fig. 5**

Summary average data for each insert type; Ra values are shown after a removal of 171,500 $mm^3$



## Experimental plan at high cutting speed

The results presented above show that, for cutting tests of Ti6Al4V up to MRR 300 mm$^3$/s and up to $v_c$ 50 m/min, there is virtually no difference in the behaviour of the inserts L and LC, i.e., no effect of the DCT on high performance coated carbide tools. In order to verify whether this behaviour is still valid at higher material removal rates, a new experimental plan has been designed and conducted with cutting speed increased to the following three levels: 62, 70 and 79 m/min. The cutting speeds are determined according to ISO 3685, which suggests a ratio of 1.12 between two subsequent levels of cutting speed for carbide tools, in wear related studies. Two replicates for every experimental condition have been performed. The feed rate has been kept constant at the highest level of the previous plan (0.3 mm/rev). The depth of cut has been increased to 1.5 mm and kept constant, with a resulting MRR that ranges up to nearly 600 mm$^3$/s.

Figure 6 and Table 5 summarise the results of the resulting 12 experimental runs. It can be noted that the cryogenically treated insert shows a longer tool life than the untreated one, in particular at higher cutting speeds. When $v_c = 62$ m/min, both inserts present a tool life of about 8 min. At 70 m/min the cryo-treated “LC” lasts about 9 % longer than the untreated “L” while at 79 m/min the difference is further increased to 30 %. These differences are statistically significant, as confirmed by an ANOVA test. In Fig. 6 the total removed material right before tool failure at the various cutting speeds is plotted. The difference increases with the increase in cutting speed and this is a very interesting and important result: cryogenically treated inserts could have important applications in high speed machining. Furthermore, this result is not in agreement with previous studies conducted on different work materials [19, 20]. Regression curves with quadratic terms on $v_c$ are added to the graph, indicating that the two inserts might start to behave differently when a cutting speed of about 65 m/min is exceeded.

**Fig. 6**

Vc vs. removed material for insert “L” and “LC”

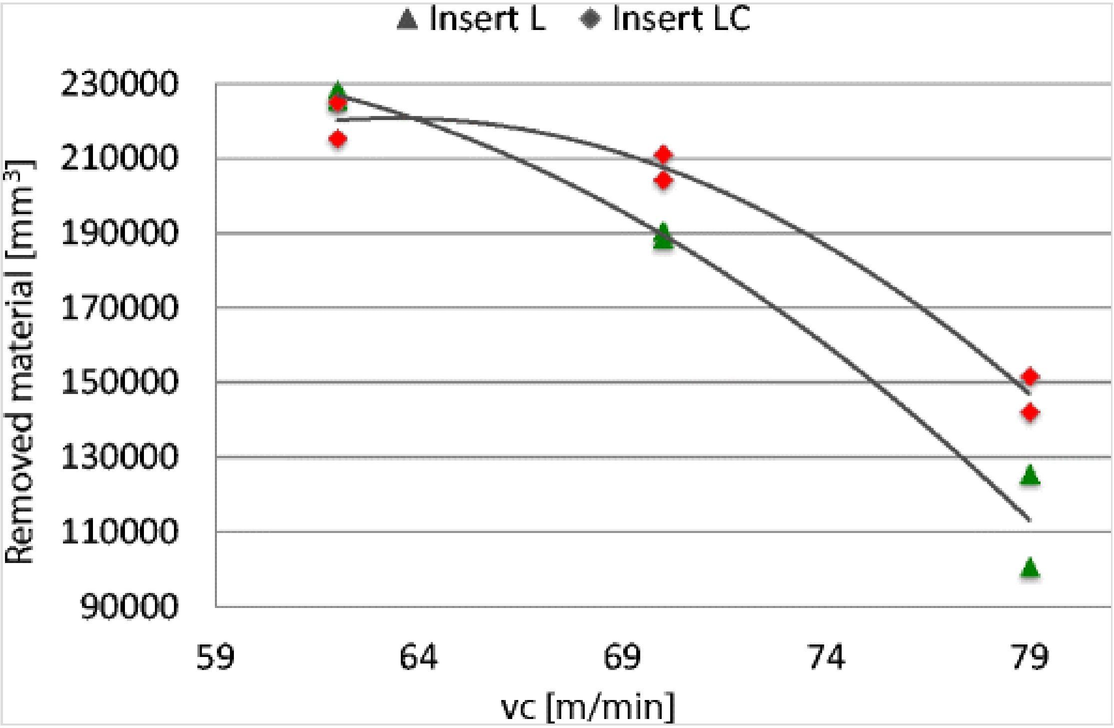


**Table 5**

Tool life data for the high speed experimental plan

| | Vc [m/min] | T [min] | | Vc [m/min] | T [min] |
|---|---|---|---|---|---|
| Insert L | 62 | 8.2 | Insert LC | 62 | 8.1 |
| | | 8.1 | | | 7.7 |
| | 70 | 6.0 | | 70 | 6.7 |
| | | 6.1 | | | 6.5 |
| | 79 | 2.8 | | 79 | 4.3 |
| | | 3.5 | | | 4.0 |

This different behaviour is also illustrated by the sequence of pictures in Figs. 7 and 8.

**Fig. 7**

Evolution of flank wear for Insert “L” at Vc = 79 m/min

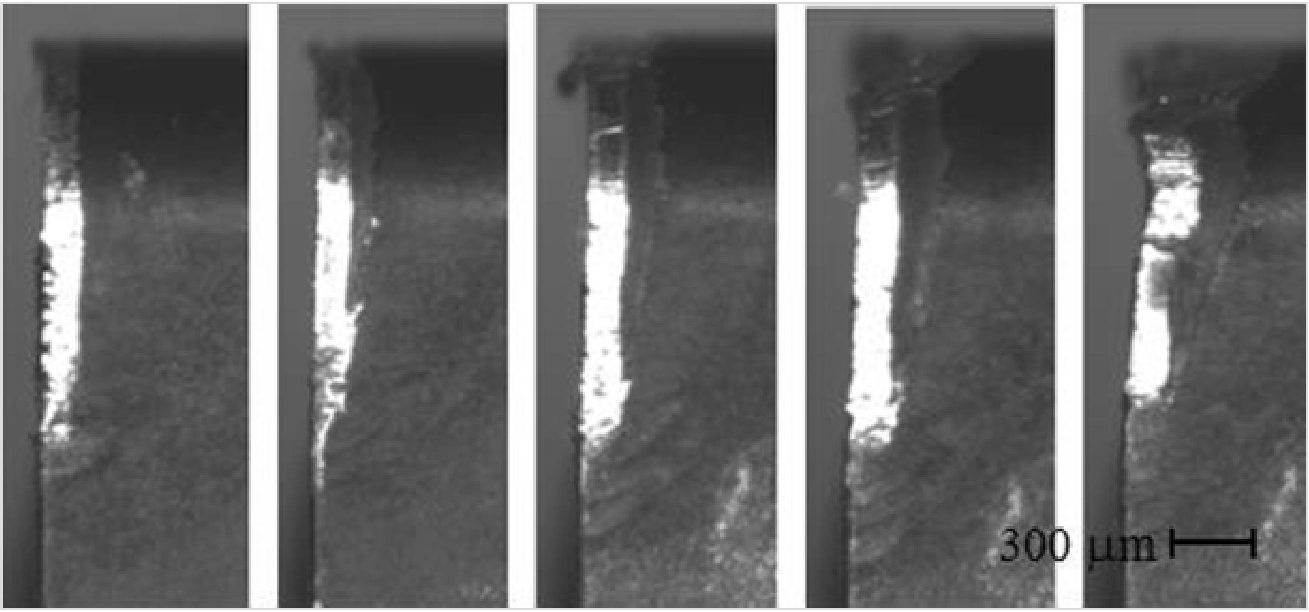
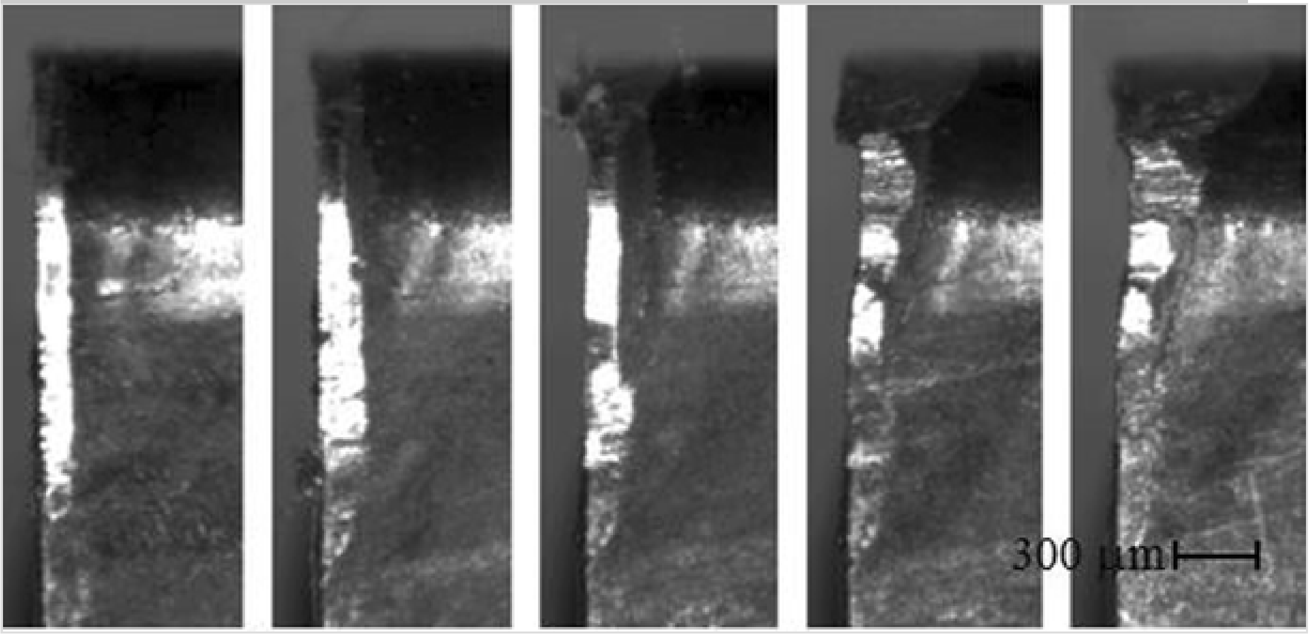


**Fig. 8**

Evolution of flank wear for Insert "LC" at Vc = 79 m/min



## *Tool wear mechanisms analysis*

In this section of the paper the results of the analysis of the wear mechanisms occurring during the experimental campaign are reported. To understand the wear mechanisms differences between the cryogenically treated (LC) and untreated (L) tools, both coated with a single layer TiAlN coating of about 4 μm in thickness, the tools were used until their life end. The wear surfaces were examined under a scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS). The different images taken along the tool edge were composed using MosaicJ plugin for ImageJ [30]. Both the rake and the flank wear are clearly visible: the main evident differences can be appreciated by primarily focusing on the wear of the tool rake.

In Fig. 9 the morphology of the worn surfaces can be appreciated. In particular it can be noted that for both tools a part of the tool coating has been removed and a titanium layer has adhered to the tungsten carbide substrate. The “LC” tool presents a much more evident plastic deformation on the tool nose radius, as an indication of greater toughness. In Figs. 10 and 11 the scanning electron micrographs of both insert are reported. Each letter refers to a different material:

**Fig. 9**

SEM morphological scanning of worn tools (vc 79 m/min): L on the *left side* and LC on the *right*

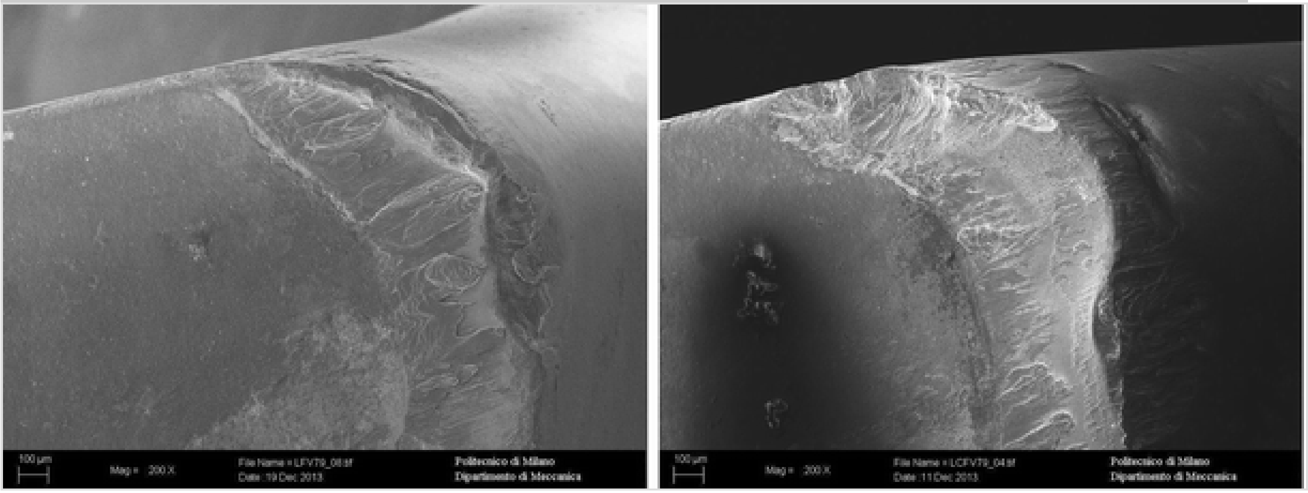


**Fig. 10**

Scanning electron micrograph of insert L (*a*: unworn TiAlN coating layer, *b*: tungsten carbide substrate, *c*: titanium)

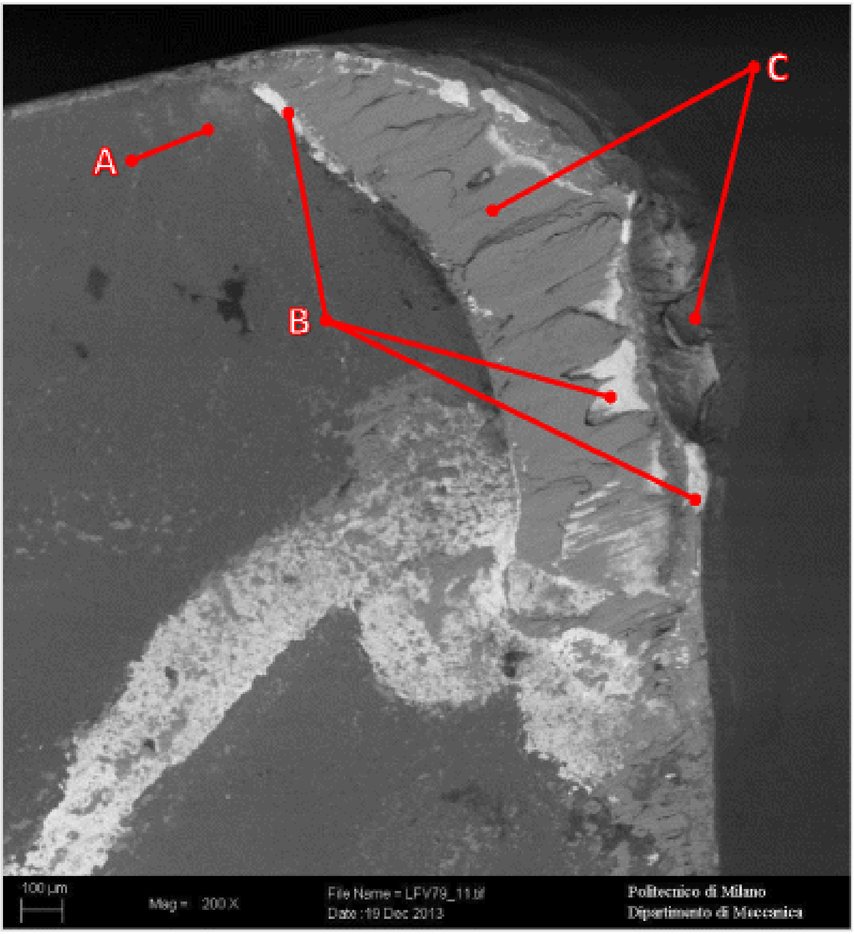
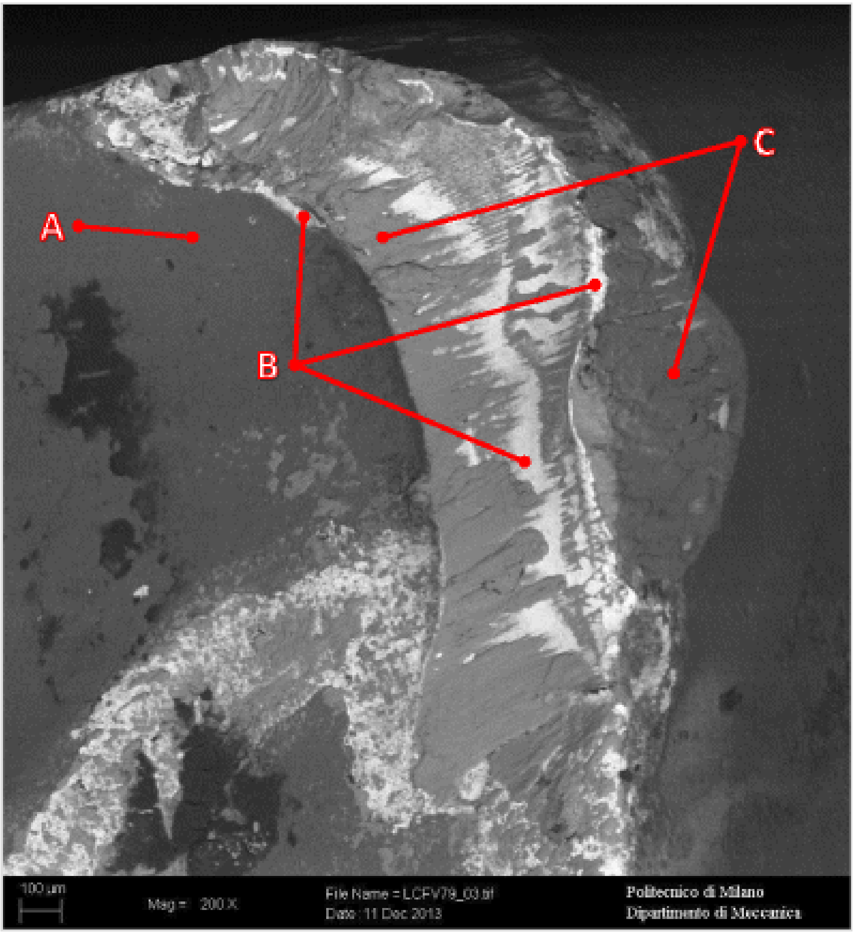


**Fig. 11**

Scanning electron micrograph of insert LC (*a*: unworn TiAlN coating layer, *b*: tungsten carbide substrate, *c*: titanium)



- A: unworn TiAlN coating layer
- B: tungsten carbide substrate
- C: titanium

The coating layer zone closer to the cutting edge has been removed, probably during the initial wear stage, by the friction between the chip and the tool. From that stage, the workpiece material starts to adhere to the substrate: when a portion of this material is removed from the tool due to the mechanical action involved in the material removal process, it brings with it part of the substrate causing the crater enlargement. The coating delamination is quite a common phenomenon in machining of “hard to cut materials”. Nouari et al. [31] observed a severe delamination of multi-layer CVD-coated (chemical vapor deposition) alloyed carbide tool in dry titanium alloy milling. Also Jawaid et al. [8] observed that coating delamination was one of the wear mechanisms that occurs in titanium milling.

The cryo-treated insert LC seems to present a lower titanium adhesion phenomenon on the rake face. The tool flank wear mechanism appears similar for both tools.

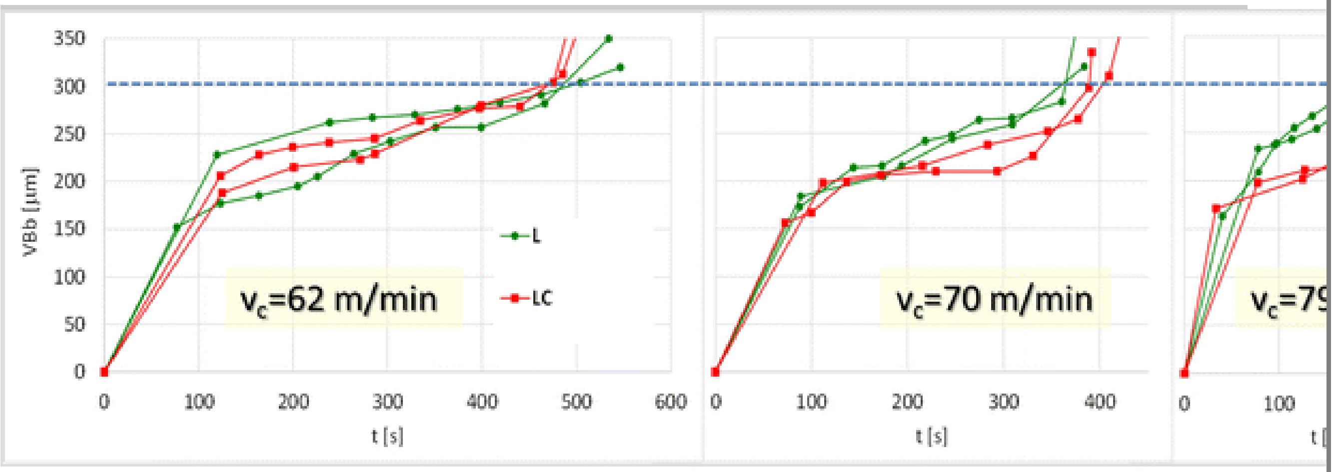
### *Explanation of observed improvements at high cutting speed*

Previous studies [25–27] have suggested that the cryogenic treatments induce microstructural modifications of the WC substrate of the tools. According to the literature, these modifications should form a denser and tougher matrix in the core material. Hardness measurement performed directly on the uncoated WC substrate have shown that, after DCT, the matrix is not only tougher and denser (as shown by previous studies), but it is also harder, with an increase of nearly + 7 %. As already shown in Section 2, if testing the hardness of the PVD coating layered over the substrate, there is an increase due to DCT of nearly +11 %, comparable with the hardening of the substrate. One positive effect of cryogenics is therefore the hardening of both the tool coated surface and its core material. Furthermore, it is well known that very hard (and fragile) coatings such as the one used for inserts “L” and “LC” tend to fracture at higher levels of stress, i.e., to last longer, if the hardness of the underlying substrate is increased [32]. In other words the DCT helps to increase the strength of the tool substrate which, in turn, increases the toughness (i.e., the resistance to fracture and delamination) of the coating. This moderately increased level of surface hardness and toughness should help in explaining a moderate increase of resistance to wear.

Figure 6 and Table 5 show that there is an increasing advantage of cryogenically treated tools with increasing cutting speed. This behavior clearly emerges only at higher values of cutting speed. In Section 2 we have shown that the speed does not significantly influence the cutting forces, but it does influence the chip segmentation frequency. It influences the tool temperature too, and this is most likely the explanation of why the cryogenically treated tool outperforms the “L” tool only at higher $v_c$. When the cutting speed (i.e., temperature) is smaller, the substrate of untreated tools provides sufficient strength to the coating, and the tool exhibits a moderate slope of the $VB_b$ vs. time curve in the central region ($v_c$ equal to 62 or 70 m/min in Fig. 12). On the contrary, when the cutting speed (i.e., temperature) is higher, the strength of the untreated WC matrix decreases, it is not able to sustain the outer layers and the tool rapidly deteriorates with a steep slope of the $VB_b$ vs. time curve ($v_c$ equal to 79 m/min in Fig. 12).

**Fig. 12**

$VB_B$ vs. cutting time for inserts L (*round dot*) and LC (*square dot*)



# Conclusions

The typical failure of tools in titanium machining is due to flank wear of the inserts. A WC insert (“LC”), coated with a hard and thick TiAlN layer, further hardened by a deep cryogenic treatment (DCT), has been tested and compared to its untreated version (“L”) and to a coated tool that can be considered an industrial standard for the rough turning of aerospace titanium (“S”).

Tool wear ($VB_B$) differences among all inserts are marginal at very low cutting speeds, but become more and more evident as cutting speed increases. When cutting speed exceeds 40 m/min, the S insert (with hardness close to 1880 HV) is outperformed by the other tools. When cutting speed exceeds 65 m/min, the L insert (about 2040 HV) is outperformed by the cryogenically treated LC insert (about 2260 HV). The improvement is correlated to an increase of the strength of the WC substrate of the inserts after a cryogenic treatment.

Scanning electron micrographs performed on the L and LC tools showed a different adhesion of the workpiece material to the tool rake face, with this phenomenon being smaller for the cryogenically treated insert.

In conclusion, it appears that relevant improvements of productivity of titanium turning can be obtained at moderate to high cutting speed if a DCT is applied, even on a high performance PVD coated insert.

## Acknowledgments

The authors wish to gratefully acknowledge the very precious contribution of several engineers and technicians who helped in both the experimental activity and the analysis of the results: Valerio Mussi and Corrado Buroni of MUSP for their valuable help in the conduction of experiments; Marco Costanzi of Tifast for his advices and analyses on the titanium alloy, Alessandro Farinotti of Lafer for his unmatched expertise on the coatings, Gaetano Pittalà and Gianluigi Bezzon of Sandvik for their help in the selection of the tools and the experimental conditions. This work has been partly funded by the Tecnopolo of Piacenza.

## References

1. Olovsjö S, Hammersberg P, Avdovic P et al (2011) Methodology for evaluating effects of material characteristics on machinability—theory and statistics-based modelling applied on alloy 718. Int J Adv Manuf Technol 59:55–66. doi: 10.1007/s00170-011-3503-3

2. Ezugwu EO, Wang Z (1997) Titanium alloys and their machinability—a review. J Mater Process Technol

3. Hughes JI, Sharman ARC, Ridgway K (2006) The effect of cutting tool material and edge geometry on tool life and workpiece surface integrity. Proc Inst Mech Eng B J Eng Manuf 220:93–107. doi: 10.1243/095440506X78192

4. Wyen C-F, Wegener K (2010) Influence of cutting edge radius on cutting forces in machining titanium. CIRP Ann Technol 59:93–96

5. Jawaid A, Che-Haron CH, Abdullah A (1999) Tool wear characteristics in turning of titanium alloy Ti-6246. J Mater Process Technol 92–93:329–334. doi: 10.1016/S0924-0136(99)00246-0

6. Ezugwu EO, Da Silva R (2005) Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies. Int J Mach Tools Manuf 45:1009–1014

7. Özel T, Sima M, Srivastava AK, Kaftanoglu B (2010) Investigations

on the effects of multi-layered coated inserts in machining Ti–6Al–4V alloy with experiments and finite element simulations. CIRP Ann Technol 59:77–82

8. Jawaid A, Sharif S, Koksal S (2000) Evaluation of wear mechanisms of coated carbide tools when face milling titanium alloy. J Mater Process Technol 99:266–274

9. Jaffery SHI, Mativenga PT (2011) Wear mechanisms analysis for turning Ti-6Al-4V—towards the development of suitable tool coatings. Int J Adv Manuf Technol 58:479–493. doi: 10.1007/s00170-011-3427-y

10. Ibrahim GA, Haron CHC, Ghani JA (2009) Surface integrity of ti-6al-4v eli when machined using coated carbide tools under dry cutting condition. Int J Mech Mater Eng

11. Nouari M, Calamaz M, Haddag B, Girot F (2013) Analysis of coating performances in machining titanium alloys for aerospace applications. Int J Mach Mach Mater 13:158–173

12. Srivastava AK, Iverson J (2010) An experimental investigation into the high speed turning of Ti-6Al-4V titanium alloy. Int Manuf Sci Eng Conf 401–408

13. Liu Z, An Q, Xu J et al (2013) Wear performance of (nc-AlTiN)/(a-Si3N4) coating and (nc-AlCrN)/(a-Si3N4) coating in high-speed machining of titanium alloys under dry and minimum quantity lubrication (MQL) conditions. Wear 305:249–259. doi: 10.1016/j.wear.2013.02.001

14. Prengel H, Jindal P, Wendt K et al (2001) A new class of high performance PVD coatings for carbide cutting tools. Surf Coat Technol 139:25–34

15. Hosokawa A, Shimamura K, Ueda T (2012) Cutting characteristics of PVD-coated tools deposited by unbalanced magnetron sputtering method. CIRP Ann Manuf Technol 61:95–98

16. Evans C, Bryan JB (1991) Cryogenic diamond turning of stainless

steel. CIRP Ann Manuf Technol 40:571–575

17. Shokrani A, Dhokia V, Muñoz-Escalona P, Newman ST (2013) State-of-the-art cryogenic machining and processing. Int J Comput Integr Manuf 26:616–648. doi: 10.1080/0951192X.2012.749531

18. Mohan Lal D, Renganarayanan S, Kalanidhi A (2001) Cryogenic treatment to augment wear resistance of tool and die steels. Cryogenics (Guildf) 41:149–155

19. Gill S, Singh H, Singh R, Singh J (2010) Cryoprocessing of cutting tool materials—a review. Int J Adv Manuf Technol 48:175–192

20. Gill SS, Singh J, Singh H, Singh R (2011) Investigation on wear behaviour of cryogenically treated TiAlN coated tungsten carbide inserts in turning. Int J Mach Tools Manuf 51:25–33. doi: 10.1016/j.ijmachtools.2010.10.003

21. Yong AYL, Seah KHW, Rahman M (2006) Performance of cryogenically treated tungsten carbide tools in milling operations. Int J Adv Manuf Technol 32:638–643. doi: 10.1007/s00170-005-0379-0

22. Yong AYL, Seah KHW, Rahman M (2006) Performance evaluation of cryogenically treated tungsten carbide tools in turning. Int J Mach Tools Manuf 46:2051–2056. doi: 10.1016/j.ijmachtools.2006.01.002

23. Yong J, Ding C (2011) Effect of cryogenic treatment on WC–Co cemented carbides. Mater Sci Eng A 528:1735–1739. doi: 10.1016/j.msea.2010.11.009

24. Gill SS, Singh R, Singh H, Singh J (2009) Wear behaviour of cryogenically treated tungsten carbide inserts under dry and wet turning conditions. Int J Mach Tools Manuf 49:256–260. doi: 10.1016/j.ijmachtools.2008.11.001

25. Thakur D, Ramamoorthy B, Vijayaraghavan L (2008) Influence of different post treatments on tungsten carbide–cobalt inserts. Mater Lett 62:4403–4406. doi: 10.1016/j.matlet.2008.07.043

26. SreeramaReddy TV, Sornakumar T, VenkataramaReddy M, Venkatram R (2009) Machinability of C45 steel with deep cryogenic treated tungsten carbide cutting tool inserts. Int J Refract Met Hard Mater 27:181–185. doi: 10.1016/j.ijrmhm.2008.04.007

27. Gill SS, Singh J, Singh H, Singh R (2011) Metallurgical and mechanical characteristics of cryogenically treated tungsten carbide (WC–Co). Int J Adv Manuf Technol 58:119–131. doi: 10.1007/s00170-011-3369-4

28. Holman J (2011) Experimental methods for engineers. Mcgraw-Hill Series in Mechanical Engineering. 800

29. Montgomery DC (2001) Design and analysis of experiments, 5th ed. New York

30. Thévenaz P, Unser M (2007) User-friendly semiautomated assembly of accurate image mosaics in microscopy. Microsc Res Tech 70:135–146. doi: 10.1002/jemt.20393

31. Nouari M, Ginting A (2006) Wear characteristics and performance of multi-layer CVD-coated alloyed carbide tool in dry end milling of titanium alloy. Surf Coat Technol 200:5663–5676

32. Holmberg K, Mathews A (1994) Coatings tribology: a concept, critical aspects and future directions. Thin Solid Films 253:173–178. doi: 10.1016/0040-6090(94)90315-8